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INFRARED RADIOMETRIC SCANNING SYSTEM FOR FLEXIBLE PACKAGE SEAL DEFECTS

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Army Natick Laboratories
Natick, Massachusetts

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Feasibility, performance, and optimization studies, plus realization of the nature of the defects anticipated in package seals under actual production conditions, have shown that the infrared scanner is sensitive, versatile, and reliable. The radiometer can measure temperature changes as small as 0.5°C, and with this sensitivity is able to detect seal defects as small as 3.5-mil thread in available packaging materials at rates commensurate with current package production rates. The operating principles of the scanner

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19.	LINK A Role	LINK A Weight	LINK B Role	LINK B Weight
Detection	8		4	
Defects	9		4	
Seals	9		9	
Containers	9		9	
Flexible Food Packaging	9		9	
Flexible	0			
Infrared Scanners	10			
Scanners	10			
Infrared Radiometry	4			
Preservation	4		4	
Food			4	
Tests			8	
Inspection			8	
heating			10	
Radiation			10	

20. Continued:

could be directly applied to a large variety of packaging materials with expected results similar to those found for the tri-laminate material.

Although we have discussed only one application today, food packaging, there are many other applications for a seal defect detection system of this nature. For example, tremendous interest has been shown in our work by leading manufacturers of pharmaceutical supplies. In fact, wherever reliable package seals are critical, we feel that this type of equipment has application. To our knowledge, this scanner is the first nondestructive seal inspection device with sufficient operati g speed capability to be feasible for use on production lines. Hopefully, future generations of equipment of this type will make significant contributions in the area of packaging and nondestructive testing.

FOREWORD

Earlier exploratory development had established that an infrared scanning technique was feasible for the detection of small defects such as occluded matter, voids, or wrinkles in flat flexible package seal areas. The initial application of this procedure was the four and one-half-inch long, three-eighths-inch wide closure seal of packages of thermoprocessed foods where occluded food particles, grease, water, or the presence of voids or wrinkles could result in loss of package integrity.

The feasibility effort provided data on which to base a design for a prototype scanner suitable for on-line use to align, scan, and evaluate (accept or reject packages) package closure seals. A prototype machine has been fabricated to Natick's requirements and approval by the Barnes Engineering Company. This report describes the operation of this apparatus and presents the results of studies to establish its capabilities.

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INFRARED RADIOMETRIC SCANNING SYSTEM

FOR

FLEXIBLE PACKAGE SEAL DEFECTS

CHAPTER I. Feasibility Studies

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Finding flexible-packaging flaws via infrared

Faulty seals in pouch packages of sensitive foods and drugs can be detected by this new non-destructive test that points way to a simple production-line quality check

By R. A. Lampi, F. Fiori and K. H. Hu

A considerable problem with modern pouch packages has been the assurance of effective heat seals due to product contamination in the seal area. This becomes even more critical in dealing with thermally processed foods in pouches.

These sealing flaws can now be detected by a new non-destructive infrared test method developed by the General Equipment and Packaging Laboratory of the U.S. Army Natick (Mass.) Laboratories. Initial investigations were meant to find optimum infrared-detecting and operating conditions for the equipment to determine the feasibility of applying this test in-line on form/fill/seal/equipment.

The authors: Mr. Lampi is a research physical scientist and both he and his associates are employed at the Packaging Div., General Equipment & Packaging Laboratory, U.S. Army (Natick) Laboratories, Mass., where they are studying control techniques for heat-processed foods in flexible packages.

Knowing that the closure of a filled, sterile pouch is most critical, members of the laboratory ran a series of experiments with an infrared radiometric microscope and have found a way to predict the reliability of this vital final seal.

Procedure

Using three basic components, here is how infrared seal-testing works: (1) a moving carriage holds the sealed package and passes the seal across (2) a narrow-beam flameless torch that heats the seal uniformly so that, (3) the IR radiometric microscope (located opposite the heat source) can measure directly the temperature of the flexible material along the heated strip.

The key component in testing sealed plastic food pouches is a Model RM-2B infrared microscope, designed and built by Barnes Engineering Co., Stamford, Conn., that permits measuring of the tem-

Figure 1. *Infrared microscope (left) that measures residual heat in film pouch (center), applied by heating torch (right). Pouch is held in jig that has slit over top seal area.*

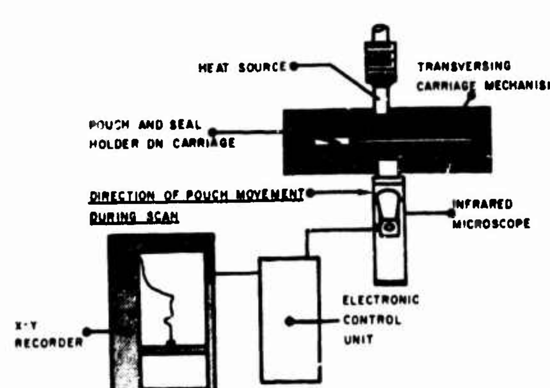

Figure 2. *Schematic of measuring system shows hookup between infrared scanner and recorder that plots microvolt impulses from heat in pouch seal. Defects or impurities cause sharp change in electrical pattern.*

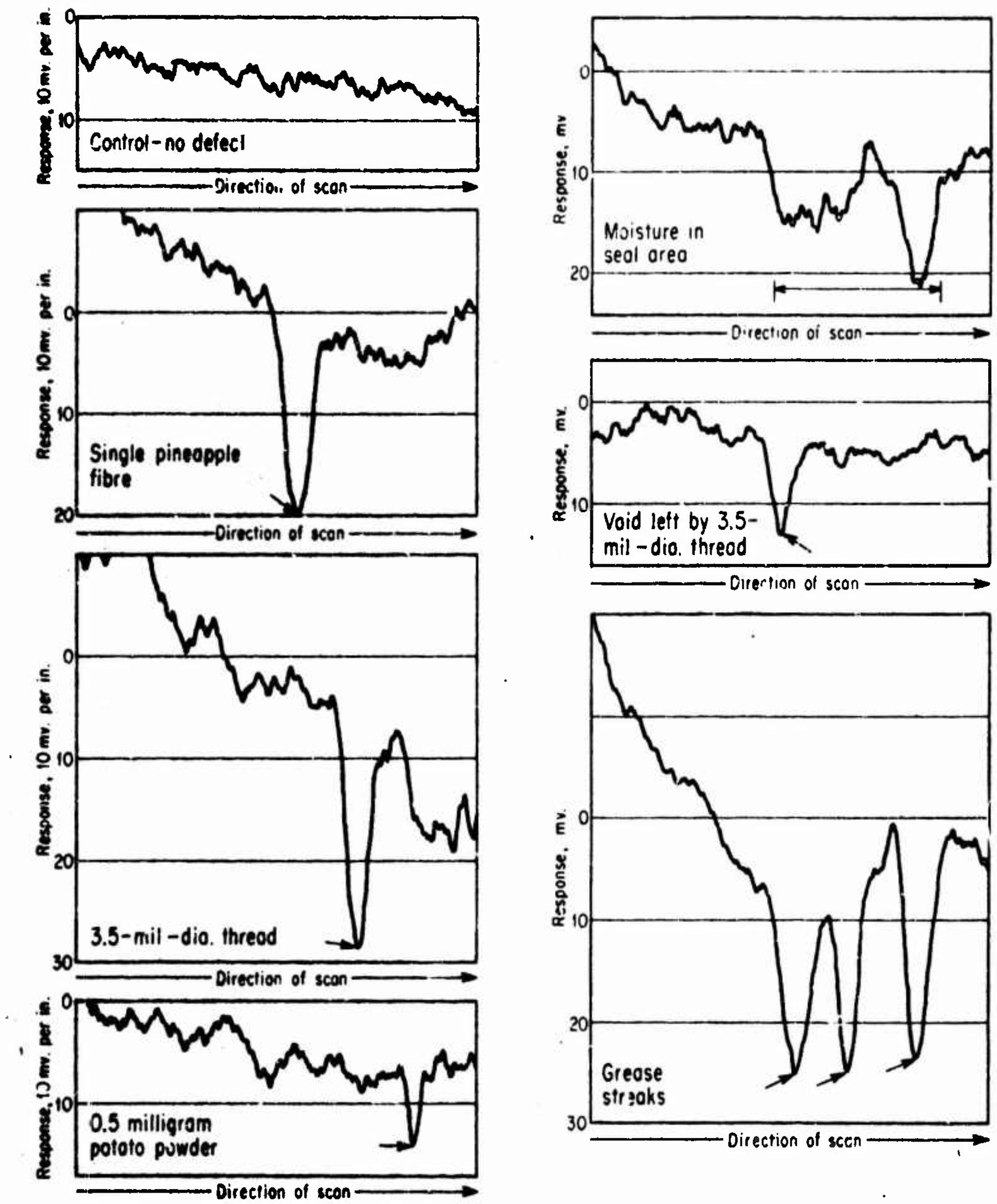

Figure 3. *Plots of various defects uncovered by infrared scan, compared with no-defect control seal in film pouch.*

perature of any object between 15 and 165 deg. C., with increments as fine as 0.5 deg. C. It is shown in Figure 1 and schematically presented in Fig. 2.

Radiant energy given off by the object under test is focused on a germanium hyperimmersed thermistor bolometer (infrared detector) that provides a small voltage change for any change in radiant energy. Amplified electronically, this change ultimately emerges as a voltage variation that drives a direct reading meter or can be recorded. One major advantage of the IR microscope—indeed, of any infrared instrument—is that no physical contact with the target is necessary. Thus, the measurement, itself, does not disturb test conditions.

Theoretically, IR equipment does not measure temperature; rather, it determines radiance, which is a function of both temperature and emissivity. However, when dealing with a material of known and relatively constant emissivity, this valve is set on the instrument's emissivity-input adjustment; the instrument is then calibrated to read temperature directly. If sample emissivity is not known, it is determined by setting the sample at a known temperature and reading off the emissivity setting required to bring the instrument output reading to that same temperature.

Pinpoint heat came from a Model FT-200 flameless torch with an 0.125-in.-diameter nozzle, manufactured by Henes Manufacturing Co. Air flow and temperature are adjustable, but early trials showed that minimum air flow (2 cu. ft. per hour) was adequate. Measured at 0.25 in. from the nozzle tip, air temperature ranged between 67 and 187 deg. C. for all runs; seal surface temperature, as determined by the IR microscope, varied between 36 and 60 deg. C. To create and maintain a flat seal surface, thus keeping two vital distances constant (seal-to-heat-source and seal-to-microscope), a simple holder was designed as part of the traversing carriage. It consists of two aluminum plates with two 0.5-in. slots to expose the seal area, as well as rectangular wells in the center to accommodate the filled pouches. After the package is clamped in this holder, each assembly under test is mounted on the pedestal of the traversing carriage.

When the heat-seal is uniform in thickness, heat dissipates at a uniform rate and miscroscope output is essentially uniform. However, if there is an air bubble or foreign matter entrapped in the seal, the thermal impedance at that spot is different. Heat does not dissipate at the same rate and there is a sharp change in the temperature indication on the instrument's direct-reading output meter or strip-chart recorder. It takes only a 0.5-deg. C. variation in heat to cause a distinct change in output signal, which is readily provided by entrapped impurities or voids in the seal.

Smallest defects noted during the many test runs conducted at this laboratory were 0.5 mg. of potato granules and freeze-dried pork fibres; a 3.5-mil-diameter thread and a void left by withdrawing that thread. In addition, grease streaks and moisture were readily detected. Table I shows a list of other contaminants picked up by the IR microscope, and the instrument's response to thermal impedance caused by these impurities. Inspection of some of the charted responses (Fig. 3) reveals the sharpness of the variation produced by an embedded contaminant or a void, and the ease with which the defect can be spotted.

Table I: Simulated seal defects and response of Infrared microscope to thermal impedance of defects

Simulated defect	Size/quantity	Response-mv. replicate I	Response-mv. samples II
Freeze-dried pork fibres	0.5, 1.0 mg.	16	18
	1.0 mg.	40	
Cooked celery fibre	Single fibre	26	
Pineapple fibre	Single fibre	17	30
Sugar crystals	Single	14	
	(3 each)	18	
Dehydrated potato powder	0.5 mg.	7	14
	1.0 mg.	14	
Grease (oleomargarine)	Streaks	20	16
Moisture	Large droplets	11	Off scale
Wrinkle (created by making one seal surface longer than the other)	⅛-in. difference in length of seal surfaces	10	
Void (created by sealing in thread or wire and withdrawing same)	3.5 mil* dia. thread	9	8
	26-mil dia. wire	Off scale	
Nylon thread, dry	3.5-mil* dia.	17	10
	5.5-mil dia.	13	
	8.0 mil dia.	11	

*Nominal diameter of thread or wire prior to sealing.

Packages tested

Two types of packages currently used for thermally processed foods were tested. Both had an outer layer of 0.5-mil polyester and a middle layer of 0.35-mil aluminum foil. The inner, heat-seal layer was either 3-mil high-density polyethylene or 3-mil modified polyolefin. Both constructions reacted identically to the IR scanning technique.

Defects occur most frequently in the final seal for two reasons: (a) This is the opening through which food is inserted and (b) stresses of sealing a bulging, filled pouch are less controllable, so that the ensuing seal is much more likely to be irregular or wrinkled.

Except for specific runs with production pouches —or runs to determine the effect of other methods— all seals were made with a Sentinel Model 12-12AS sealer, pressing a constant-resistance heated bar against a silicone rubber anvil (45 durometer). Packages were closed at 450 deg. F., 40 psig. pressure and 1 sec. of dwell, yielding seals capable of withstanding subsequent thermal processing and handling.

Other sealing methods were also evaluated, but with less satisfactory results. For example, a four-bar metal seal against Viton rubber covered with Teflon fibre-glass cloth was tried, heating both elements to 300 deg. F. for a dwell time of 2.5 sec. Apparently, because of the two heated elements, the deliberately inserted thread was greatly compressed, thus achieving fibre-imbedding so complete that it provided no noticeable change in heat transfer during testing. The IR scan did not pick up this "flaw."

Similarly, ultrasonic seals are hard to scan with an infrared microscope. The knurled surface of such a seal causes strong and erratic background signals, making it difficult to distinguish temperature signal from noise.

Broadening the scan

Under normal conditions, the spot size of a focused RM-2B IR microscope with a 15X lens is 0.0028 in. On the other hand, the width of a package seal, according to present specifications, is at least 0.375 in. Therefore, it is conceivable that a once-over scan might miss the type of defect that does

Table II: Effect of variations in heat-source distance, seal scanning speeds and heat-source temperatures First series

Distance, heat source to package, in.*	0.25				0.5			
Seal scanning speed, in. per sec.	0.4		0.8		0.4		0.8	
Heat-source temp., deg. C.	67	145	67	145	67	145	67	145
Defect signal, Mv.†	20	22	26	34	14	22	14	15
Maximum noise effect, Mv.	4	3	10	10	6	12	8	7
Usable signal, Mv.**	16	19	16	24	8	10	6	[illegible]

*X-Y recorder time sweep, 1 in. per sec.
†Recorder signal sensitivity, 20 Mv. per in.
**Usable signal, defect signal less maximum noise effect.

not extend all the way across the width of the seal.

Because multiple scanning of eacl package, to be certain of a sound seal, would complicate procedures—particularly in a production setup—another approach was tried. The microscope was deliberately defocused to a spot size of 0.032 in. Not only did this broaden the base of the signal response without a decrease in signal strength, but it also smoothed out background noise. Even when the spot was increased to 0.25 in., a distinct response was still perceived, although at the expense of some signal smoothness and magnitude (as shown in Fig. 4). For production purposes, a setting of 0.25-in. seems quite practical, permitting the user to check 67% of a seal width in a single scan with reliable and repeatable results. However, accurate alignment of a package is vital, so that signals will not be picked up from non-seal areas.

Other factors that influence test results include: background noise, scanning speed, heat-source temperature, heat-source-to-package distance and lateral distance between the heat source and the IR microscope's field of view.

Similarly, distance from heat source to package was varied, to note the effect on flaw-finding. Best results were obtained with a distance of 0.25 in. Heat-source temperatures ranged from 127 to 187 deg. C. without appreciably changing the findings. Tables II, III and IV show the mathematical results of several test series.

Background noise stems from a variety of random signals that reduce the signal-to-noise ratio. Among them are minor variations in the material's emissivity, minute irregularities in the packaging materials and on the heat-sealer surface, even stray air currents. Stray air currents were held to a minimum during test, but the other random factors are uncontrollable. Fortunateiy, the IR microscope provides a sufficiently high signal-to-noise ratio, so that background noise does not overshadow or confuse the main signal.

The traversing carriage was especially designed by Barnes to accommodate the sealed package and provide constant scanning speeds from 0.8 to 1.14 in. per second. Even though background noise at the higher speed was three times as high, it did not significantly detract from the instrument's sensitivity. In fact, it seemed likely that equally useful results could be obtained with even faster scans.

In all cases, results were measured in millivolts deflection above the background level. Actual signal strength, by itself, was not critical because the aim was to find a variation in signal. As long as any one level was maintained, the seal was uniformly sound. However, when a sudden change in temperature was indicated by a sudden and very pronounced change in signal, the microscope had located a problem area in the seal. Invariably, when this seal area was pulled open, some contaminant, void or wrinkle was discovered. Generally, defects caused temperature differences of about 1 deg. C. But even one embedded pineapple fibre, for example, caused a 7 deg. C. temperature change.

Conclusions

Except for two cases—ultrasonic seals and seals made with opposing heated elements—findings at our laboratory show that the IR microscope provides a valid means for checking the integrity of sealed plastic packages. The new technique was able to detect defects from a variety of causes—including grease, moisture, occluded food fibres or particles, threads, voids and wrinkles.

Defects as small as 0.5 mg. of freeze-dried meat fibres, single crystals of sugar and voids left by withdrawing a 3.5-mil thread were detected. It is difficult to visualize any significant incidence of defects smaller than these occurring in commercial operation. Sensitivity, therefore, seems adequate.

Several types of commercial-caliber hot-bar seals suitable for llexibile packages of thermally processed foods were tested. These were made on laboratory sealers and at least one type of production-line sealer. Defects were detected in each case.

Table III: First optimization series, analysis of variance

	Degrees of freedom	Sum of squares	Mean square	Test statistic (F††)
Column*	1	231.12	231.12	22.55
Row†	1	0.12	0.12	0.012
Layer**	1	28.12	28.12	2.74
C times R	1	10.13	10.13	0.99
C times L	1	6.13	6.13	0.60
R times L	1	3.13	3.13	0.35
Error	4	40.5	10.25	—

*Column, distance between heat source and seal surface.
†Row, scanning speed.
**Layer, temperature of point heat source.
††$F_{0.95}$ (1,4)=7.71; $F_{0.99}$ (1,4)=21.20.

Table IV: Effect of variations in heat-source temperature and seal-scanning speeds Second series

Scanning speed, in. per sec.*	0.8					1.14	
Temperature of heat source, deg. C.	127	145	165	175	187	145	175
Defect signal, Mv.†	90	85	70	85	95	65	65
Maximum noise effect, Mv.	20	15	25	25	35	15	15
Usable signal, Mv.**	70	70	45	60	60	50	50

*The time sweeps of the recorder differed for the two scanning speeds as follows: 0.8 in. per sec. seal scan: 1 in. per sec. sweep. 1.14 in. per sec. seal scan: 2 in. per sec. sweep.
†Recorder signal sensitivity: 50 Mv. per in.
**Usable signal, defect signal less maximum noise effect.

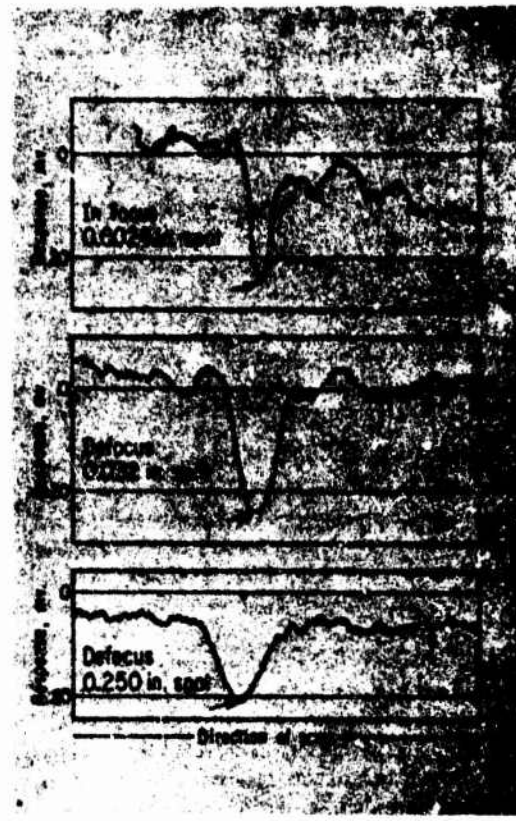

Figure 4. *Effect of defocusing infrared beam to cover wider area of film heat-seal is shown in two degrees, compared with focused control, in detection of single sugar crystal.*

A defect signal of 50 to 70 mv. above maximum background noise (a signal-to-noise ratio of 3.3:1) was obtained and interpretation of results, in general, was easy. Our tests showed us that commercial seals did not cause an inordinate amount of background noise.

Reproducibility, to give similar scan results on repeats of a single sample or on replicate samples of the same defect, was good.

Defocusing—in some runs—to enlarge the field of view and permit a single scan to cover a larger portion of the total seal did not lessen detecting capability.

Heat-source-to-seal distance definitely affects the signal, but heat-source temperature and scanning speed, within the range studied, had no significant effect.

A set of typical operating conditions follows:

1. Heat-source-to-microscope distance: $\frac{1}{16}$ in.
2. Distance from heat source to package-seal surface: ¼ in.
3. Scanning speed: 1.14 in. per sec.
4. Heat-source temperature: 145 to 175 deg. C. at air flow of 2 cu. ft. per hr.

Based on these findings, the laboratory is recommending further study, leading eventually to production-line testing. Specifically, the relationship between a minute defect and the integrity of the seal has to be investigated, to obtain an answer to the question: "If a speck is occluded in the seal but is completely surrounded by a bona fide bond, does this lower true seal integrity?" Similarly: "If a dual, opposing hot-element sealer is used, does a small but totally occluded foreign particle still represent a threat?"

In addition, thinking of the production man's needs, the question of scanning speed must be analyzed to develop practical working limits. Efforts must also be directed toward eliminating or reducing background noise, by shielding against stray air currents or perhaps by uniform preheating of the seal. Finally, any other mechanical means or devices which will speed seal analysis, will have to be evaluated. □

CHAPTER II. Prototype Description

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Inspects Package Seals*

Infrared device detects flaws in flexible package seals at rates of 60 packages per min. Reliable test could be used for heat-processed foods in "flexible tin can"

A PROTOTYPE inspection unit to spot defective package seals is undergoing evaluation at the U.S. Army Natick Laboratories. To date, tests indicate that the unit can reliably detect faulty seals caused by entrapped food particles, grease, moisture, air bubbles and wrinkles in the seal at inspection rates up to 60 packages per min. Among the defects it detects are those caused by inclusions as small as 0.5 mg of freeze-dried meat fibers; single crystals of sugar; and voids left by withdrawing a 3.5 mil thread.

How Infrared Inspection Works

Any defect in the package seal impedes heat flow across the seal more than a perfectly bonded section. In the test, the underside of the seal is uniformly heated for a brief period. The top surface then becomes evenly warmed except that it will be measurably cooler in those areas containing a defect. Detection of any unexpected cool areas is cause for rejection.

Infrared energy is radiated by all objects in proportion to their temperatures, hotter areas emitting more total energy. This energy, collected by an optical system, is concentrated upon the infrared detector, which converts it to an electrical signal. Processed by solid-state electronics, the output produces an accurate temperature reading on the front panel meter or on a chart recorder

G. B. ORDWAY and G. L. SCHULZ
Barnes Engineering Co. Stamford, Conn. and U S Army Natick Laboratories, Natick, Mass

The inspection system (Barnes Engineering Co.) is divided into 3 major sub-systems:

The mechanical conveyor aligns the pouches, passes them through inspection, then into accept or reject chutes.

The infrared flaw detection system generates a beam of focused light to heat the underside of the seal, then measures temperature gradients along the upper surface of the seal.

The electronic logic system examines the information generated by the infrared system, determines acceptance, and actuates the conveyor to direct the package into the proper chute.

Operating Details

In operation, a flexible package is dropped onto a crossfeed belt which moves it into the main carrier. As the clamp of the main carrier closes, it leaves the seal area exposed through a slot. Packages that are torn, folded, or mis-aligned leave a gap in the slot. These conditions are detected by a photocell and are cause for rejection.

Next, the package passes into the infrared inspection zone, where the carrier serves to keep the seal flat and in the radiometer focal plane. First the underside of the seal is heated by a beam of focused radiation, after which a radiometer measures the temperature of the top side. When the package passes out from under the radiometer and is unclamped, the logic system has all the information it needs. The package is then accepted or rejected.

The infrared flaw detection system inspects a 0.25-in. wide band along the entire length of the

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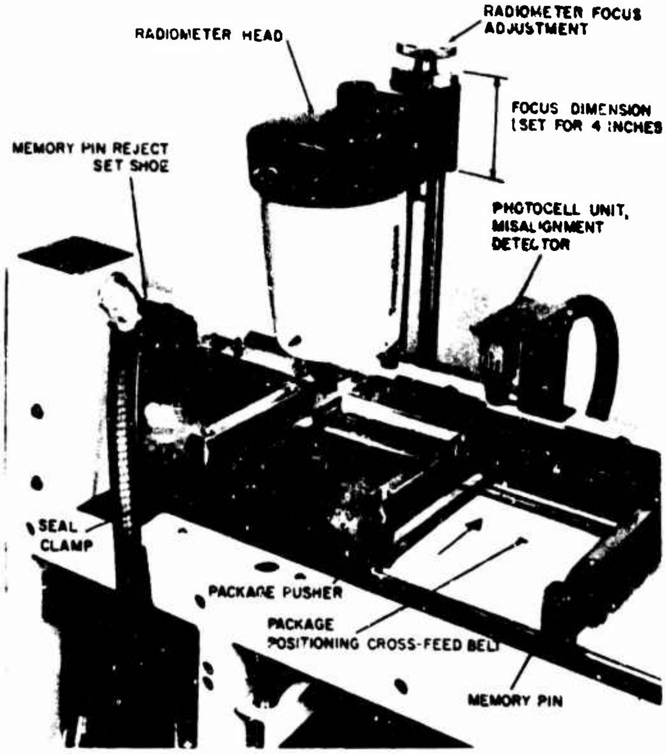
INSPECTION SYSTEM to detect sealing flaws is being evaluated at U S Army Natick Labs



CLOSE-UP of inspection station shows carriers which transport packages under radiometer head

package closure seal. Heat is supplied by focusing light from an electric lamp onto the seal. To permit optimal heating, the lamp can be moved in a plane perpendicular to the radiometer viewing axis. The movement is in two directions, perpendicular and parallel to the direction of conveyor motion. Also, by being able to regulate the lead distance between the movable heat source and fixed radiometer check-point, significant readings can be obtained, regardless of changes in conveyor speeds. Heat source and radiometer head are unitized on drawer rails and can be rolled out for service without disturbing lamp alignment or focus.

In the radiometer electrical output, a defect in the seal region causes a dip in the signal voltage. The signal is electronically processed and fed to logic circuitry. If this signal falls between predetermined levels for a specified minimum time, the logic circuitry identifies the package as defective. If the seal temperature does not exceed a predetermined minimum, the package is identified as a reject because it may not be sealed.

Important To Army

Flexible packages for heat-processed foods offer a convenient and economical way to transport and store food. When substituted for a can, the flexible package offers a 40% reduction in container weight, 25% less space in shipping, and it easily fits into pockets of field clothing. In addition, it causes no injury if fallen upon.

Much progress has been made in materials and machinery for thermally processing food in pouches. A typical material is a lamination of 0.5 mil polyester, 0.35 mil aluminum foil, and 3 mil modified polyolefin. When suitable materials are properly bonded and formed into a package, they do not delaminate during thermal processing, do not impart a foreign flavor or odor to the food, and are capable of meeting FDA requirements.

In the established processing, 4½ x 7 in. pouches are filled with product, air is expelled, and the open end sealed between heated pressure bars. Sealed pouches are racked about one inch apart loaded into a retort, and water processed. Thirty minutes at 250F is usual for 6 oz packages of meats and vegetables. For most fruits, 15-20 min at 212F is sufficient. Overriding air pressure of 20 psig is supplied when retort temperature reaches 212F to prevent internally generated steam from bursting the package seals. Packages processed in this manner do not delaminate, have heat seals that resist pulls of at least 7 lb per in. of seal, and withstand shipping and rough field usage.

Because flexible packages must be filled at high speed through a comparatively small opening, preventing contamination of the seal area has been relatively unsuccessful. A steam flush after filling generally succeeds in removing the contaminants, and heat-seal bars with a curved surface produce an acceptable seal in spite of slight contamination in the area. Nevertheless, a reliable test to assure integrity of the critical closure seal is still needed. (End)

CHAPTER III. Performance and Optimization Studies

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Automatic Infrared Radiometric Scanning to Detect Flexible Package Seal Defects

RAUNO A. LAMPI, NORMAN D. ROBERTS, AND FREDERICK A. COSTANZA

Abstract—For military applications, the use of a flexible package as a replacement for metal cans, particularly for operational rations, has been of interest for many years. Progress has been made to the point where the logistical, functional, and durability advantages of a flexible package of commercially sterile ready-to-eat food, the so called "Flex-Pack", to replace the 300 × 200 (3" diameter by 2" height) can in combat rations have been proven. The U.S. Army Natick Laboratories (Department of Defense) is in the final stages of testing the reliability of a flexible packaging system for single-serving portions of heat-processed foods [1]. Unlike the frozen, boil-in-bag system, these packages of food are shelf stable and commercially sterile and, therefore, the integrity of the package must be positively maintained to prevent bacterial entry and subsequent spoilage of the food product.

INTRODUCTION

Throughout the "Flex-Pack", Fig. 1, development program, the major cause of package failure has been attributed to defective closure seals. Of the defective closure seals identified from examination of approximately 53,000 packages, occluded matter resulting from the package filling operation was found to be the primary cause of failure. Although the total failure rate including all causes was only approximately 0.3%, when public health and economic aspects were considered, this figure was judged too high. As part of an extensive program to assure the reliability of this packaging system, studies were undertaken to develop a nondestructive method and machine capable of reliably detecting defective closure seals.

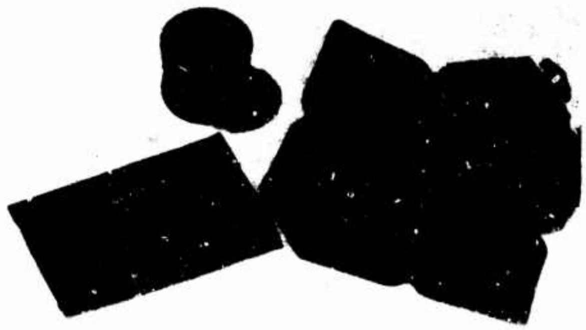

Fig. 1. Ration component in can and flex pack.

Feasibility studies showed that infrared radiometric scanning of transiently heated seal surfaces could pinpoint a variety of seal defects such as small occluded particles, wrinkles, voids, and noncontinuous fusion across the seal width, Fig. 2.

Based on the findings from preliminary feasibility studies [2] and known infrared technology [3], requirements for a

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The authors are with the U.S. Army Natick Laboratories, Natick, Mass. 01760.

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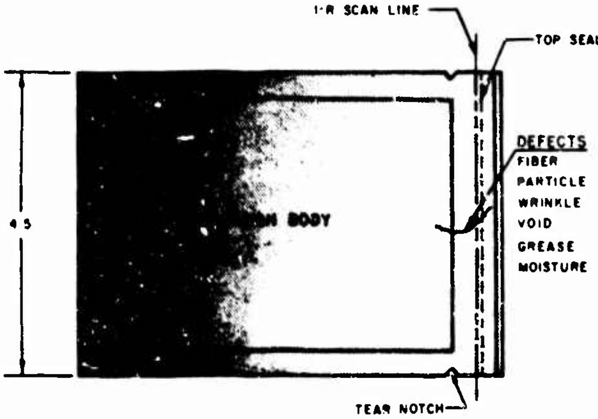

Fig. 2. Schematic of seal defects.

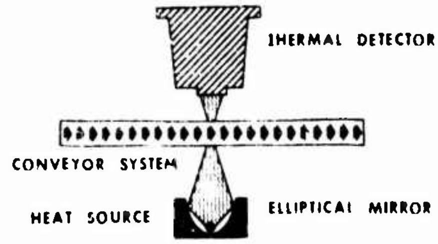

Fig. 3. A simplified schematic of the main features of the infrared scanner. The arrow filled rectangle represents the edge of a package seal being transported between the heat source and detector.

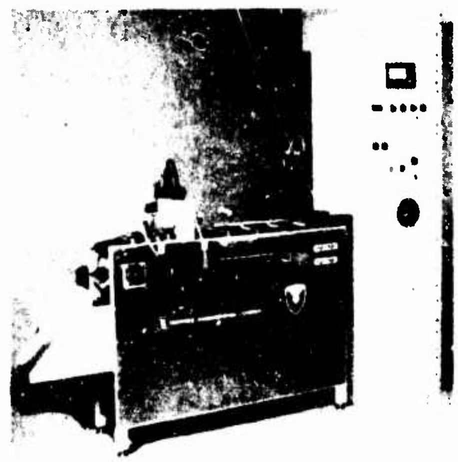
Fig. 4. The prototype infrared scanner with the transport mechanism on the left and the electronics console on the right.

prototype automated package seal inspection machine were prepared and a contract was awarded to Barnes Engineering Company. The prototype machine, designed, built, and performance-tested by Barnes under this contract to the established requirements, has been in operation for approximately one year and has undergone extensive testing at the U.S. Army Natick Laboratories. This machine is designed to scan one seal only—the closure seal, as shown in Fig. 2—where, as the result of the filling operation, the great majority of defects may occur. It is the aim of this paper to describe the operation of the machine, and to present some details on the findings of Barnes and Natick studies on its capabilities.

DESCRIPTION OF MACHINE

The infrared scanner operates on the principle of thermal impedance, Fig. 3. A conveyor carries each package such that its closure seal passes between a heat source and a thermal detector. The lower surface of the seal is heated by the radiant heat energy from a halogen tungsten lamp which is focused on the package seal by an elliptical mirror. Any defect within the seal will impede the flux of heat passing through the seal causing a decrease in temperature on the upper seal surface. This temperature is measured over the length of a seal by a thermal detector, and its electrical output constitutes a temperature profile of the upper seal surface.

The scanner is composed of two main functional groups, Fig. 4. The first is the transport mechanism which receives, positions, and secures the package for a scan of the closure seal; the second is the detector along with the electronics console which processes the signal from the thermal detector and determines the acceptability of the package seal.

The transport mechanism positions packages by means of a cross-feed belt, Fig. 5. This belt drives the closure seal end of a package between the jaws of a clamp on the conveyer. A linear cam alongside the conveyer closes the clamp on the periphery of the package seal securing the package to the conveyer. The clamp contains a $\frac{1}{4}''$ wide slot positioned to leave an unobstructed view of the seal, and through which the seal is scanned. This positioning device design was based on the assurance of prominent packaging equipment manufacturers

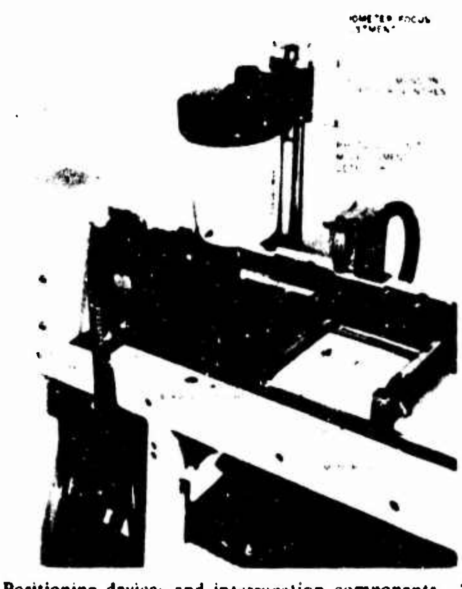
Fig. 5. Positioning devices and interrogation components. There is a small light source under the conveyor beneath the photocell unit by which the unit detects misalignment.

that the seal would be parallel to the end of the package and accurately positioned from the end of the package.

Beyond the transverse belt is a photo electric cell which interrogates each clamp as it passes beneath the cell, Fig. 5.

The purpose of the interrogation is to protect the thermal detector by determining whether the clamp contains a package and if so whether the package is properly aligned. If the clamp does not contain a package or if the package is misaligned, or even torn or grossly punctured, the photocell will detect light from a light bulb beneath the clamp and will prevent a scan from taking place. The photocell controls a shutter in front of the objective lens of the thermal detector and prevents an unnecessary scan by keeping the shutter closed during the scan period. By preventing the scan under these conditions the photocell protects the thermal detector from the direct rays of the heat source which could damage the detector's electronic components. Whenever the photocell prevents a scan, whatever is in the clamp, if anything, is rejected.

The thermal detector is mounted on the transport mechanism next to the photoelectric cell, Fig. 5. The thermal detector, or radiometer, used on the scanner is a modified Thermal Master, Model IT4, made by the Barnes Engineering Co. It contains a hyperimmersed thermistor bolometer as an infrared detector and an internal heat source as a temperature reference. The reference heat source, called a cavitrol, is maintained at 45°C ± 0.1°C and is used to provide response stability. A rotating chopper in the radiometer interrupts the incoming radiaiton at a 100 Hz rate, allowing the detector to alternately "see" the target radiation and radiation reflected by the chopper from the cavitrol. The two readings are electronically combined to produce an output corresponding to the target temperature.

The Thermal Master is also filtered for optimum performance when scanning the "flex-pack" material, which has a polyester film as an outer layer.

To meet our requirement to scan a $\frac{1}{4}$"-wide band over the length of the package closure seal, the radiometer contains a specially designed lens which provides a field of view (spot) 0.25" in diameter at a working distance of 1.25". In the standard Thermal Master the spot size is 0.030" in diameter. In addition to inspecting the full $\frac{1}{4}$" band in a single pass, the use of a larger spot size also tends to minimize the effect of isolated, small thermal irregularities without a significant loss of defect detectability.

A graph of the electrical output of the radiometer, as it scans a defective seal, bottom Fig. 6, shows small normal temperature fluctuations in addition to the large trough in the center which represents the temperature depression resulting from the defect.

For ease of maintenance and adjustment, the radiometer, heat source, and mirror are mounted on the transport mechanism in a pull-out drawer, Fig. 7.

The heat source is a Sylvania tungsten halogen projector lamp which, under anticipated scanning conditions, will be operated well below its rated capacity of 500 watts. It is powered by a voltage source which is continuously variable from 0 to 140 volts. This allows the level of heating to be adjusted for different packaging materials and scanning rates.

To concentrate and direct the heat, a mirror, in the shape of one half of an elliptical cylinder, is used. This elliptical mirror collects approximately Pi steradians of radiation from the lamp and focuses it as a line image on the lower surface of the seal being scanned. The image is approximately 0.2" wide by 1" long, with the long dimension perpendicular to the direction of seal travel.

The image of the heat source on the lower seal surface is not

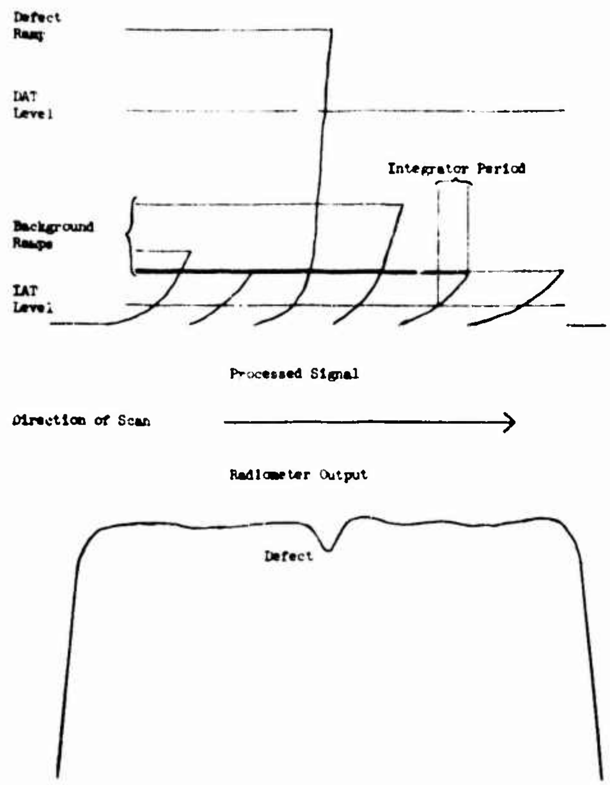

Fig. 6. Voltage ramps resulting from I-R Radiometer signal processing.

Fig. 7. Pull-out drawer containing heat lamp and mirror and on which is mounted the thermal detector.

Fig. 8. Accept-reject mechanisms: memory pin, reject solenoid with pin setting shoe, and pickup switch.

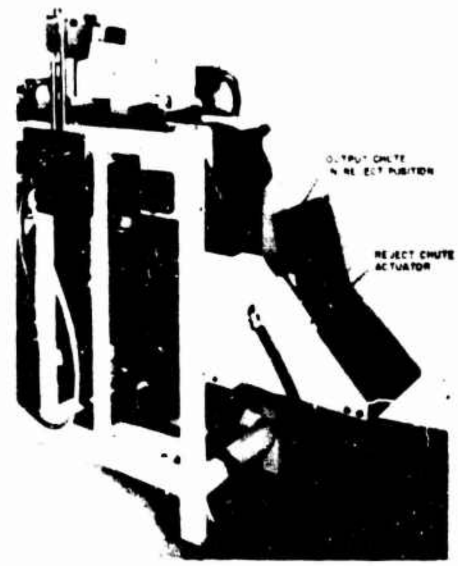

Fig. 9. Diversion mechanism, output chute in raised or reject position.

directly opposite the sopt on the upper seal surface being viewed by the radiometer, but is slightly upstream of the radiometer field of view with respect to the direction of package travel. The displacement between the heated area and the area being viewed by the radiometer is called the lead distance and is adjustable from 0.0" to 1.0". With this adjustment, the time interval between the heating of the lower seal surface and the temperature measurement of the upper seal surface can be varied to produce the optimum temperature distribution, that is, one effecting the greatest temperature drop at the site of the defect.

Each carriage of the conveyer on the transport mechanism contains a pin holder and memory pin which is pre-set by a cam during each conveyer cycle to project from the inboard side of its holder, Fig. 5. This is the pouch accept position for the memory pin. A reject signal from the electronics console causes displacement of the pin which then contacts the memory pin pickup switch, Fig. 8. The pickup switch contact energizes a pouch diversion mechanism. In the prototype scanner, this mechanism is a gate in the output chute which is raised for diversion and remains lowered for defect free packages. Other diversion mechanisms can be used, Fig. 9.

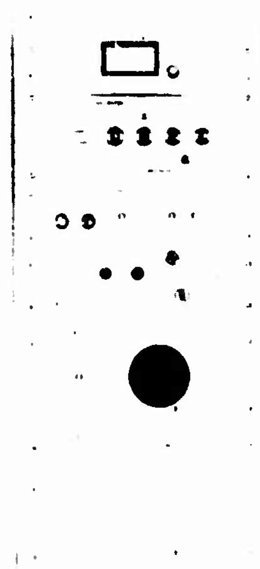

Fig. 10. Electronics processing console.

The second functional group includes the electronics console which contains the electronic processing equipment and is connected to the transport mechanism by a twenty foot length of cable, permitting the console to be located away from any wet area in a food plant, Fig. 10.

All of the controls for the infrared scanner (with the exception of the lead distance and scan speed controls, which are located on the transport mechanism) are located on the console. The signal processing is controlled by four potentiometers located on the detection control panel, Fig. 10. The potentiometer on the right is the minimum temperature detection control. With this control a minimum temperature can be established which must be exceeded by the package seal being scanned in order for the scan to be processed. This control is used to reject packages which are completely unsealed since the upper side of an unsealed package remains virtually unheated by the heat lamp.

The first three potentiometers, from left to right in Fig. 10, are the period, initiate area threshold, and detect area threshold controls.

The signal processing consists of converting the radiometer output into a series of rapidly increasing voltages, or ramps, of varying peak heights, Fig. 6, which depend on the rate of change of temperature along the seal length. The period and initiate area threshold controls set the voltage range within which these ramps are generated.

The lower graph is that of the radiometer output. The depression in the center is the result of a seal defect. The upper graph is that of the processed signal showing that the voltage ramps increase in magnitude at the defect. Changing the period and initiate area threshold controls changes the number and heights of the ramps.

The detect area threshold control sets a voltage level which, if exceeded by a voltage ramp, results in a reject signal, Fig. 6. This signal actuates the memory pin setter which rejects the package.

The controls, together with a variable scan speed which can be adjusted from about twenty to about sixty packages per minute (two to six inches of seal length per second), allow the infrared scanner to be adapted to a variety of packaging materials, defect criteria, and scanning rate needs.

The packaging material for which the infrared scanner was designed, is a tri-laminate composed of a 3-mil inner lamina of heat sealable modified polyolefin, an 0.35-mil barrier layer of aluminum foil, and a scuff resistant 0.5-mil outer lamina of polyester film. The adhesive between the aluminum foil and polyester film contains an olive-drab pigment which significantly increases the emissivity of the packaging material. The emissivities of several lots of this type of material from two manufacturers were measured and were found to be in the range from 0.80 to 0.84 in the 2 to 20 micron wavelength range.

This packaging material undergoes a phase change at a temperature of 110°C. At temperatures exceeding 110°C, this phase change absorbs some of the heat flux, resulting in a decreased transmission rate and consequently, a decreased defect detectability. To maximize defect detectability, which requires the maximum heat flux, the power output of the heat source was reduced to produce maximum seal temperatures less than 110°C at the maximum scanning rate of 6"/sec. Below the maximum limit, however, the power output of the heat source is variable.

EXPERIMENTAL WORK

The experimental work performed with the machine to date has consisted of basic performance testing and optimization studies. Performance testing was necessary to determine that the infrared scanner met the contract acceptance criteria. A prerequisite to performing such tests has been selecting and quantifying defects for purposes of (1) assuring that the test procedure will find defects we would expect in real life and (2) providing a basis for the optimization effort.

The feasibility tests had been performed with a variety of actual and simulated defects that, at best, were semi-quantitative. Since no better, more realistic approach had been devised, these same types were consequently selected and used for the preliminary performance tests on which acceptance of the prototype machine was based. These are listed in TABLE I, along with numbers of each prepared and used for the actual performance tests. It is felt that rarely, if ever, would smaller defects (human hair, based on our measurements, is 2.5 to 3.5 mil in diameter) be encountered. It is fully acknowledged that a defect such as a 5.5-mil diameter thread may not be that dimension after sealing.

The preliminary performance tests were performed without extensive equipment optimization effort. The selection of the settings was based on experience and conditioned by the acceptance criteria: 90% correct decisions when the packages shown in TABLE I were run through at any time of a two hour operational cycle. The results of these early performance tests are shown in TABLES II and III. Inert materials were used to simulate two types of foods since the seal defects violated package integrity and actual food would have spoiled. The acceptance tests indicated that pouch alignment and exposure

TABLE I
SEAL DEFECTS USED FOR PERFORMANCE TESTS

Defect Type	Size/Quantity	Number Planned Per Typical Performance Test Run
Freeze-Dried Pork Fibers	0.5 mg.	9
Freeze-Dried Pork Fibers	1.0 mg.	9
Celery Fiber		1
Pineapple Fiber		1
Granulated Sugar Crystal	single	1
Granulated Sugar Crystal	3 each	10
Dehydrated Potato Powder	0.5 mg.	9
Dehydrated Potato Powder	1.0 mg.	9
Grease		1
Moisture		1
Wrinkle		1
Void-Seal & Withdraw Thread	3.5 mil	1
Void-Seal & Withdraw Thread	26 mil	10
Thread	3.5 mil	1
Thread	5.5 mil	1
Thread	8 mil	10
TOTAL		75

TABLE II
PERFORMANCE TEST FOR MACHINE ACCEPTANCE
4½ X 7 INCH PACKAGES OF PUMPABLE PRODUCT*

		Rate of Scan		
		20 Pkgs/Min	30 Pkgs/Min	60 Pkgs/Min
Defective Packages	Number Tested	50	150	72
	Per Cent Rejected	94%	97%	95%
Non-Defective Parts	Number Tested	50	94	55
	Per Cent Accepted	94%	96%	91%

*5% suspension of Bentonite to simulate pumpable product such as Beef Stew.

TABLE III
PERFORMANCE TEST FOR MACHINE ACCEPTANCE
4½ X 7 INCH PACKAGES OF PLACEABLE PRODUCT*

		Rate of Scan		
		20 Pkgs/Min	30 Pkgs/Min	60 Pkgs/Min
Defective Packages	Number Tested	50	141	129
	Per Cent Rejected	96%	94%	93%
Non-Defective Parts	Number Tested	50	149	117
	Per Cent Accepted	96%	94%	97%

*Alternate layers of putty and corrugated fiberboard to simulate size, density, and consistency of placeable or solid food such as beefsteak.

to the test experience was good, that a wide variety of defects could be detected at production speeds, and accuracy of decision was easily better than 90%. The machine was accepted.

The optimization studies began with the variation of lamp voltage and lead distance settings.

The lamp intensity determines the heat flux through the seal area, and the lead distance affects the time lag between the heating of the lower seal surface and the scan of the upper seal surface by the radiometer. These two variables, by controlling the transient temperature distribution, affect the scanner's defect detectability.

As a measure of defect detectability, the voltage ramps produced by the electronics processing c[illegible]itry from the radiometer output are used. The voltage [illegible]orresponding to a defect can be distinguished from [illegible] c[illegible]esponding to the normal package background by th[illegible] visual examination of an oscilloscope trace as shown in Fig. 6. By comparing the magnitudes of the defect and background ramps, a direct measure of the machine's defect detectability is obtained. These measures taken at different lamp voltage and lead distance settings define a response surface as a function of lamp voltage and lead distance. From an approximate analytical expression for this response surface, optimum operating settings can be obtained.

The lowest degree equation capable of approximating a surface with an assumed local optimum is a quadratic in both variables. The design chosen for the optimization experiments, one which fits a quadratic surface to seven treatment levels. was Doolittle's hexagonal design [4].

In this design, each of the seven levels is a pair of lead distance and lamp voltage settings. These levels must be coded by a linear coordinate transformation. The coded coordinates are such that one of the levels is given the coordinates (0, 0), is the center point of the design, and is selected on the basis of judgment. The remaining six levels are chosen so that, when transformed and plotted in their coded coordinates, they become the vertices of a regular hexagon centered on the point (0, 0). The levels and coordinate transformations are chosen so that each of the vertices are one coded unit distant from, and equally spaced around, the center point.

The advantage of the coded hexagonal design is that it lends itself to a relatively simple algorithm for calculating the six necessary coefficients of the quadratic surface. It also yields a lack of fit coefficient which can be tested for significance by the usual F test.

To find the optimum settings, a thin metal plate was used in the experiments in place of the actual packaging material. The greater thermal uniformity of the plate, compared to the laminated packaging material, reduced the random error in the experiments, giving greater accuracy with fewer replicates. The plate was 0.005″-thick shim stock, painted with a flat black lacquer in which a $\frac{3}{32}$″-wide scratch was made to simulate a defect. The temperature profile of the plate closely approximated that of a defective package seal but at an elevated temperature of 115°C.

It is worth noting in this connection that the scanner discriminates on the basis of temperature changes during a scan and not on the average seal temperature. The average temperature is important only to the extent that it enhances or reduces the temperature difference between the defect and the package background.

With the scan speed held at 40 packages per minute, the scanner response to the metal plate was measured at the seven levels of an appropriate hexagon, and an analytic approximation to the response surface was calculated. The resulting response surface, Fig. 11, resembled a broad low hump, from which was determined an optimum lead distance of 0.4″ and an optimum lamp voltage setting of 132 volts. The response surface was 3% below the optimum value at lead distance settings of 0.30″ and 0.51″ and at lamp voltage settings of 128 and 136 volts. These figures indicate the relative flatness of the response surface, and that response is not critically dependent on specific lamp voltage and lead distance settings. Because of this finding and past experience (that packaging materials and the metal plate responded similarly), the application of this technique to actual packaging materials was deferred in favor of the optimization of the signal processing variables.

The signal processing variables are the period, initiate area threshold (IAT) and detect area threshold (DAT). The period and IAT settings operate jointly to determine the number and height of voltage ramps generated by a given packaging material. The DAT is an adjustable voltage level (0.0 to 1.0 volt), which, when exceeded by a voltage ramp, effects a reject signal, Fig. 6.

The optimum period and IAT settings are those which produce the largest difference between background voltage ramp height and defect ramp height. The optimum DAT setting would then be approximately halfway between the highest expected background ramp height and lowest expected defect ramp height. This requires that the background ramp height be no higher than the maximum DAT level.

The optimum values of the period and IAT settings were determined by a procedure similar to that used for optimizing the lamp voltage and lead distance settings. That is, a quadratic approximation to the response surface was fitted to the response levels at different period and IAT settings according to Doolittle's method [4].

However, the optimum period and IAT settings were not those corresponding to the maximum of the response surface. It was found that an increasing response (defect ramp minus background ramp) was accompanied by an increasing background ramp voltage and that near the maximum response the background voltage ramps exceed the maximum DAT level of one volt. The optimum period and IAT settings were therefore chosen to produce a maximum response subject to the constraint that the background ramp voltage be one volt.

The results of the optimization experiment are displayed graphically in Fig. 12. The curves, "response contour lines," are curves of constant response in units proportional to the difference between defect peak height and background peak height. The contour lines show that as period and IAT are

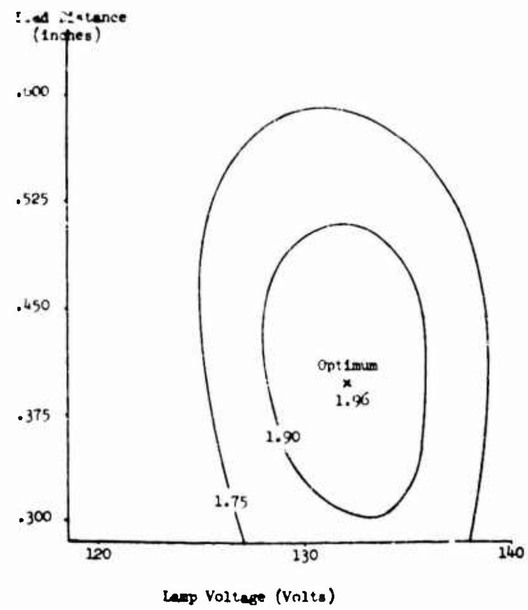

Fig. 11. Response surface as a function of lamp voltage and lead distance. The contour lines are in relative units proportional to the difference between defect peak height and background peak height.

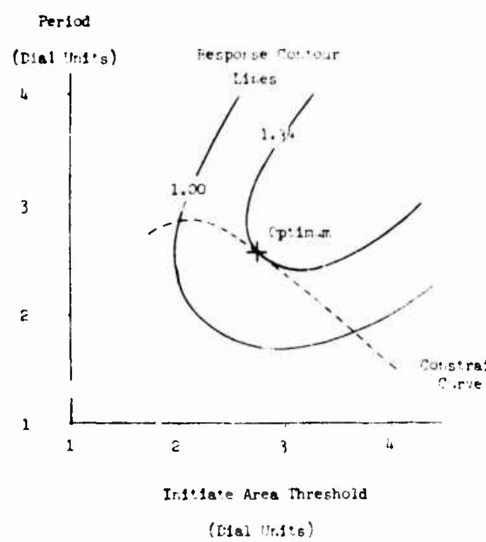

Fig. 12. Response surface as a function of period and initiate area threshold. The contour lines are in relative units proportional to the difference between defect peak height and background peak height.

increased the response level, in general, increases. The dashed curve is the constraint curve. At period and IAT settings that plot on this curve, the background peak height is one volt. At period and IAT settings that plot to the upper right of this curve, the background height is greater than one volt and, at points to the lower left, the background neight is less than one volt, showing that, in general, the background level increases with increasing response. Since the maximum DAT setting limits the background height to one volt, the optimum period and IAT settings are limited to those settings which plot either on, or to the lower left of, the constraint curve. The optimum point is indicated on the graph by an *X*. It has a response level of 1.34 units and falls on the constraint curve with period and IAT settings of 2.5 and 2.75 dial units, respectively.

The response level along the contour line marked "1.00" is 25% below the optimum response level of 1.34 relative units. The two contour lines and their respective response levels show that, in the region of the optimum, the response surface is a sharply rising ridge. The shape of this response surface demonstrates that the period and IAT adjustments are more critical in achieving optimum performance than are the lamp voltage and lead distance adjustments.

The experiments performed to date have indicated that very similar materials from two sources of supply can manifest quite different thermal response characteristics. The two materials of interest were different only in the blend of the inner 3 mil layer which, although primarily polyethylene, did contain other polymers, and in the appearance of the pigmented adhesive layer. Prior to specific optimization of detector design and nominal seal heat level, one material indicated an average signal to noise ratio 1.86 times greater than the other for similar seal defects under identical scan conditions. The inherent defect-free package material to system noise ratio was 1.7:1 for one material and 3.2:1 for the other. Design advances were made and test variables optimized to the point where the package background to system noise ratios were the same. Even then, one material, for a 5-mil thread showed a 2.25:1 defect-to-background, signal-to-noise ratio while the other was 3.1:1. These findings indicated that minor material differences could adversely affect the detectability of small defects, but that proper optimization to minimize these problems was possible.

Relative to food associated defects such as pork fibers, potato powder, sugar crystals, grease, and moisture, tests with several replicates have shown that signal ratios are easily greater than 3:1 and detection is assured. Narrow, thin grease streaks, an expected common contaminant, gave S/N ratios of 4:1 to 7:1.

CONCLUSIONS

Performance and optimization studies, plus realization of the nature of the defects anticipated in package seals under actual production conditions, have shown that the infrared scanner is sensitive, versatile, and reliable. The radiometer can measure temperature changes as small as 0.5°C and with this sensitivity is able to detect seal defects as small as a 3.5 mil thread in available packaging materials at rates commensurate with current package production rates. The operating principles of the scanner could be directly applied to a large variety of packaging materials with expected results similar to those found for the tri-laminate material.

Although we have discussed only one application, food packaging, there are many other applications for a seal defect detection system of this nature. For example, tremendous interest has been shown in our work by leading manufacturers of pharmaceutical supplies. In fact, wherever reliable package seals are critical, we feel that this type of equipment has application. To our knowledge, this scanner is the first nondestructive seal inspection device with sufficient operating speed capability to be feasible for use on production lines. Hopefully, future generations of equipment of this type will make significant contributions in the area of packaging and nondestructive testing.

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